# HEAVY TRUCKS ROLLOVER SIMULATION

**Delanne Yves ***
**Schmitt Vincent ****
**Dolcemascolo Victor ***
* Laboratoire Central des Ponts et Chaussées
** DGA/ Etablissement Technique d'Angers
France
Paper N° 444

**ABSTRACT**
**Objectives of the study** : test out the possibilities to simulate the lift-up of tires on cornering maneuvers on various vehicles with rollover propensities. This simulation is to be validated for different speeds and different payloads and center of gravity heights.

**Context** : in Europe, roundabouts are more and more built in place of traditional crossings, giving an important reduction of fatalities ; although few cases of heavy vehicles rollover have been recorded, in spite of low velocity, due to the geometric features. This study is a contribution to the comprehension of this kind of accidents.

**Ground test validation :**
A heavy truck of 10-tons payload was chosen, and instrumented with different sensors, and for safety reasons, equipped with stabilizers. The vehicle the dynamic parameters of the input vehicle file of the simulating model were adjusted on basis of elementary longitudinal and transversal ground tests. The model used is a French society SERA-CD package called PROSPER V4, which was proved to give accurate predictions, even in strong inputs [1,2]
Two different trajectories were chosen: a circle and a roundabout trajectory rebuilt on the test track.
Test parameters were different speeds and load cases, with changing center of gravity height.
Measurements, digital video and GPS-trajectory were CD-recorded : from these data, the location of the beginning of wheel lift-up was precisely determined. This information was compared to the simulation. This is considered to be the main validation criteria.

**Synthesis** : this study was the first step of the validation process. The next steps will include other rollover prone vehicles.
The package will be then used as a tool to define safety load conditions and to determine rollover stability limits ; these information would be brought to driver's attention.

**SUMMARY**

## 1. INTRODUCTION

The work presented hereafter, conducted in collaboration between LCPC and ETAS, is dealing with accident on runabouts, and simulation of rollover of heavy trucks.
LCPC (In French : Laboratoire Central des Ponts et Chaussées, English: Roads and Bridges Central Laboratory) is a research body partly financed by both the French Research and Transportation Ministries. LCPC conducts research on civil engineering (among which road and bridges is the main part) and environment. Regarding roads, apart from engineering questions, current research at LCPC is more and more concerned with road serviceability and in this framework with traffic safety. The global aim of numerous subjects being dealt with is to investigate the effect of the infrastructure features and characteristics on vehicle dynamic control (ex : [3]).
ETAS (Etablissement technique d'Angers, in English : Angers Technical establishment) carries out evaluation and trials of land combat vehicles, and is certified according to CEI 17025 norm (by French association named COFRAC) for its test activities concerning vehicle dynamic. Reducing fatal injuries or material losses during road accidents is something highly important for the French ministry of defense, too.
For LCPC, this work is a part of a research conducted for the French Directorate of Traffic and Safety (In French: Direction de la Sécurité et de la Circulation Routière , DSCR).

## 2. OBJECTIVES OF THE STUDY

In France, roundabouts are more and more built in place of traditional road intersections. This has proved to reduce vehicle collision risk and correspondingly injuries and fatalities. Although few cases of heavy vehicles (in general semi trailer) rollover have been recorded in spite of the low velocity imposed by the geometric features. This study is aiming to the comprehension of this kind of accidents.

**Picture 1** A roundabout being observed

Two tasks were defined:

- Task 1: various roundabouts on site observation of heavy vehicle drivers behavior (speed and trajectories) (picture 1)
- Task 2: test out the ability of a vehicle simulation program to detect the beginning of wheel lift up during cornering maneuvers (figure 1)

This paper is mainly concerned with task 2. In this task the simulation software named PROSPER was tested out by comparison of measured and computed dynamic parameters of a instrumented Truck for different maneuvers.

**Figure 1** Example of simulation with PROSPER

## 3. SIMULATION SOFTWARE PROSPER

### 3.1. Presentation of PROSPER software

PROSPER is a 3D-road vehicles dynamic simulation software build by SERA, R&D Company involved in road vehicles analysis and design ([www.sera-cd.com](http://www.sera-cd.com)).

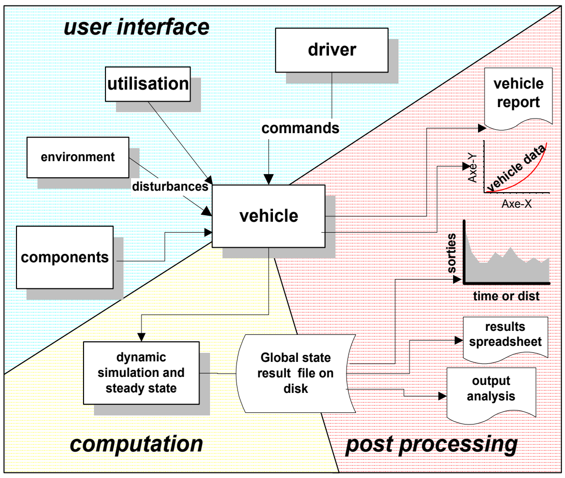



**Figure 2** Prosper in block diagram

PROSPER is basically an open loop system : inputs are driver's commands (steering, braking, and

throttle), ground and wind disturbances or any combination of both.
It has a 3D-computation engine, with **28** [1] **Degrees of** Freedom, coupled and non-linear with **800 variables.** It has been validated for all the vehicle utilization range, until performance peak and beyond the peak the loss of control (spinning) [1,2].

The software is user-friendly. It runs on PC (including notebook) with WINDOWS interface (online help, visualizations…)

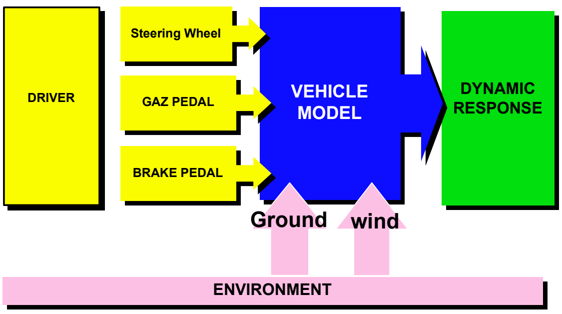
- it uses a design language (notions, names, unit, load condition…)
- it gives outputs allowing to understand: tables, graphs, animation
- it is interfaced with Microsoft Office 2000.
- the vehicle is defined by 50 windows of numerical data inputs

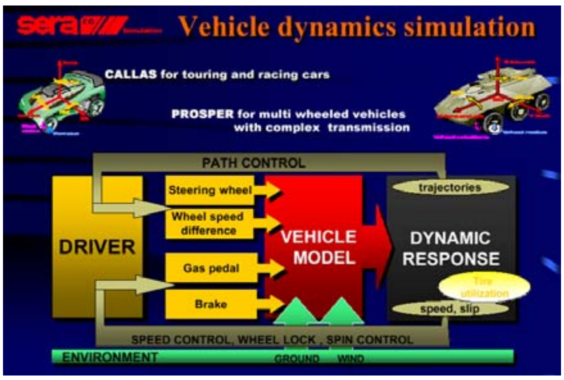
### 3.2. The 3D open & closed loops dynamic

PROSPER simulate the dynamic situation with all its complexity:

- driver's command (throttle, hand-wheel, brake) versus time
- atmospheric disturbances
- ground disturbances.

These 3 inputs types are not only added, they really interact together.
To compute performance that is car maximum obtained for an unknown optimal command, we use controls and **close loop simulation.**




**Figures 3,4** Simulation in block diagram

[1] With 10 wheels and no trailer

The number of Dof with mass is depending on the presence of a trailer and wheels number.
Beyond mass DoF, there is differential equations of first order for control or transient, and the total the order of the differential system is 90.
The main Degree of Freedom (for each vehicle) are:

- 6 body DoF
- for every wheel, rotation speed
- 1 engine rotation and one control
- for every wheel, loaded radius
- 2 steering DoF ( rack and hand wheel angle) and 2 control for the auto-driver (closed loop).

Other state variables without mass (first order equation) are per wheel :

- 2 tire transient per wheel (advanced tire module)
- brake pressure transient.

### 3.3. Preset tests list

Around 35 tests are preset, it means that you just few values are needed to specify a test.

- acceleration family:

- performance acceleration (perfect driver) with standard test extraction
- acceleration on ratios
- dynamic acceleration with several options
- passing acceleration between 2 speeds on a given ratio

- braking family:

- performance braking with perfect driver correcting trajectory and modulating the braking force, with standard test extraction
- dynamic braking with several options
- unilateral braking: half turn standing still, with - -
- max steering, inner wheels braking and throttle at max regulation braking giving ISO adhesion curve
- Mu-Split with active driver

- steering family:

- steady state cornering with constant speed: all the steering response up to lateral acceleration peak
- maneuverability: speed 2 km/h and max steering, curb and wall radii
- constant speed steering ramp
- J-turn
- power off
- optimum cornering steering envelope (best cornering at all speeds)
- constant radius
- acceleration in cornering
- acceleration on a constant radius circle
- slalom with varying amplitude and/or frequency with frequency response analysis for yaw speed, roll and lateral acceleration
- Pivot
- Unilateral braking

- straight line family:

- straight line at constant speed (ride height and consumption)
- coast down test to identify the passive forces

free steering wheel release test
- gradient and banking:

- maximum speed vs gradient
- steady state on banking with active driver to keep the straight line
- side wind sensitivity:

- steady state vs vehicle speed
- dynamics vs constant wind
- wind signal
- emergency simulation:

- braking in curve
- change lane maneuver with active driver
- combination of braking and change lane

### 3.4. Utilization conditions

- Road

Road is taken into account among 4 types, with force modulation changing the tires ones defined for optimal condition (smooth dry road).

- Passengers and/or loads

The choice of the passenger amount and fuel quantity will modify all data linked to the new load condition: new ride height, inertia, CG position, suspension travel, deflection and properties of the tire…

- Controls

Vehicle can be used with following control mode (or regulation):
- braking regulation with pedal effort modulation (simulating a perfect driver applying just the ideal force on pedal) or wheel by wheel (ABS)
- propulsion regulation (anti skidding) with engine, wheel by wheel, or "cruise control"
- with or without engine braking
- automatic or non-automatic gear shifting, time lag or not.
- sometimes, trajectory control by an active driver can be connected

## 4. TEST VEHICLE

### 4.1. Vehicle type

The validation procedure is essentially the comparison between simulation results and data acquisition on the relevant parameters : longitudinal and lateral accelerations, yaw, pitch and roll velocities and angles, suspension travels [1,2].

The vehicle selected for the validation experiments is a French military truck, from the RENAULT Trucks firm, named TRM 10000 ; it is a typical logistic vehicle, with a maximum load of about 10 000 kg. TRM is a French acronym for AWD (all-wheel drive vehicle).

It has been chosen for the following reasons:
- Its important payload ;
- The possibility to modify with large amplitudes the center of gravity height of the load ;
- All characteristics and model parameters required for the simulation are known.

Its main characteristics are the following (table 1) :

| | |
|---|---|
| weight (unloaded) | 12 000 kg |
| c.o.g height (unloaded) | about 1.20 m |
| max load | about 10 000 kg |
| number of axle | 3 |
| number of wheels | 6 |
| steering axle | front axle |
| rear axles | rear tandem |
| front suspension | semi-elliptical leaf springs (auxiliary and main springs), mechanical stops and telescopic shock absorbers |
| rear suspensions | semi-elliptical leaf spring, mechanical stops |
| tires | on and off-road tires from Michelin 14.00 x 20 |
| length / width / height | 9.2 m / 2.5 m / 3.1 m |
| wheelbase axle 1-2 | 4.3 m |
| wheelbase axle 2-3 | 1,4 m |
| max speed | about 90 km/h |

**Table 1**

### 4.2. Payload arrangements

In this study we intend to investigate the effect of different cases of load on the dynamic performances of the vehicle chosen.
A specific lest, simulating a heavy standard 20ft ISO container, has been developed.
This lest (see picture 2) consists of a steeled frame with 4 rigid boxes containing variable weights.

**Picture 2** Test vehicle TRM 10000

The boxes can be set up and down on the frame to give to the lest a center of gravity (c.o.g.) height from 0.60m to 1.85m (reference level : bottom of the lest) : in fact, the c.o.g. height of the load from ground can change from about 2.10m to 3.35m.

Such a lest has important roll, pitch and yaw inertias while 80% of the weight are on the corners of the lest.

Three cases for the lest were chosen (table 2). Inertia have been calculated by C.A.D. (Computer Aided Design) and Huyghens formula :

| Lest characteristics | n° 1 | n° 2 | n° 3 |
|---|---|---|---|
| Weight (kg) | 9400 | 9400 | 9400 |
| Load position | Low level | Average level | High level |
| c.o.g. on the z-axis (height from ground) | 2.1m | 2.7m | 3.35m |
| c.o.g. on the x-axis; 0-axis in the middle of front axle | 4.5m | 4.5m | 4.5m |
| c.o.g. on the y-axis; 0-axis in the middle of front axle | 0 | 0 | 0 |
| Roll inertia (kg.m²) | 7460 | 7160 | 8855 |
| Pitch inertia (kg.m²) | 53780 | 53470 | 55170 |
| Yaw inertia (kg.m²) | 56940 | 56940 | 56940 |
| global c.o.g height[2] (vehicle + lest) | 1.60m | 1.86m | 2.14m |

**Table 2**

### 4.3. Preliminary static tests

Firstly, precise measurements of length, weight, and axle angles as castor, camber or toe-in were done , to verify conformity of the specimen chosen for tests and ensure the accordance with the model parameters.

Then, before performing the dynamic experiments, a test using a tilt platform (picture 3) to measure static rollover thresholds was carried out.

**Picture 3** ETAS Tilt platform

[2] calculated from barycenter theory

Some definitions for this test :

- rollover threshold : tilt table angle when one of the wheels on one side of the vehicle have lost contact with the table surface.
- front roll angle : measurement of the roll angle at a rigid point in front of the vehicle (i.e. here : on the front bumper) ; this measurement is made when the vehicle reaches the rollover threshold
- rear roll angle : similar to the front, on the rear bumper.

The initial level of front and rear angle is determined when the tilt platform angle is equal to 0°.
Results of the tilt table measurements are given in table 3.

| Lest number | n° 1 | n° 2 | n° 3 |
|---|---|---|---|
| rollover threshold | 27° | 22.5° | 18.5° |
| front roll angle | 2.75° | 5.35° | 5.7° |
| rear roll angle | 5.3° | 6.8° | 7.5° |

**Table 3**

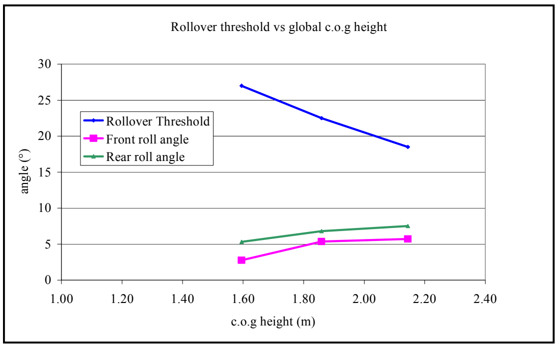



**Figure 5** Rollover threshold versus c.o.g. height

One can notice on figure 5 that the rollover threshold decreases dramatically when the c.o.g. height increases.

The difference between the front and rear angle, is mainly a consequence of chassis torsion. Furthermore, one can notice an asymptotic tendency for the highest levels of c.o.g, due to an extreme compression of suspensions.

### 4.4. Vehicle instrumentation

The TRM 10000 was fitted with a data collection systems and sensors. The main parameters recorded were driver actions (steering angle or rack displacement, throttle position, braking force) and vehicle dynamic parameters : vehicle speed, longitudinal and lateral accelerations, suspension travels, wheel rotations, braking pressures. Yaw, roll and pitch angles and angular velocities were measured, too.

Characteristics of the used sensors are given in table 4.

| device | sensor | range |
|---|---|---|
| "fifth wheel" | longitudinal velocity | 80 km/h |
| inertial reference | yaw velocity | 60°/s |
| | yaw angle | 0 to 360° |
| | roll angle | 15° |
| | lateral acceleration | 10 m.s-² |
| dynamometer steering wheel | steering wheel angle | 720° |
| | steering wheel velocity | 500 °/s |
| specific sensors | rear wheels velocity | 15 radian/s |
| | suspension height | 0.5 m |
| | gas pedal level | 0-100% |
| | engine rotation | 0-4000 rpm |
| differential GPS | trajectory | |
| weather sensor | wind velocity | 10 m/s |

**Table 4**

Data were recorded on a PC-computer, with a sampling frequency of 100 Hz and then digitally low pass filtered at 10 Hz to prevent from aliasing.

## 5. MODEL VALIDATION

### 5.1. Validation MODULE of PROSPER

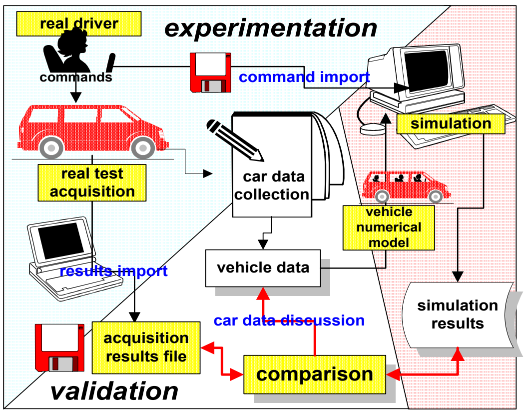



**Figure 6** Validation block diagram

On figure 6 the procedure to validate the open loop model is presented in block diagram form. Simulation inputs are the driver commands.

Validation is essentially the comparison between simulation results and data acquisition on the relevant parameters : longitudinal and lateral accelerations, yaw, pitch and roll velocities and angles, suspension travels. However this comparison is meaningful only when the model and car speeds are equal with a 1 km/h tolerance. This requires car longitudinal subsystems to be accurately modelled and to have the right parameter values : engine torque, transmission ratio, aerodynamics, rolling tyre drag.

### 5.2. Specific dynamic tests

Validations are conducted in relation to the main interests needed for the model. longitudinal accuracy were initially proved by comparison between real vehicle and model of the curves acceleration and braking.

More important were the lateral validations ; steady-state circular tests have been carried out in the conditions described on table 5 ;

| Lest number | n° 1 | n° 2 | n° 3 |
|---|---|---|---|
| Radius (m) | 30 | | |
| Vx (km/h) | 5 to 40 | 5to36 | 5to33 |
| Direction | Left/right | | |

**Table 5**

The facility for real tests was a 160m-diameter slip pad, situated at ETAS.

Validation between simulation and real test is conducted step by step with a logical order on the response parameters :

- Step 1 : validation of the forward velocity, for a gas-pedal position ;
- Step 2 : validation of the curve radius and yaw velocity obtained, for a steering-wheel input, as shown on figure 7 (example for the lest n° 3, with Vx = 32 km/h) ;
- Step 3 : validation of the lateral acceleration ;
- Step 4 : validation of the chassis motion, particularly roll angle and suspension heights ;
- Step 5 : validation of the lift-off for one wheel or tandem axle.

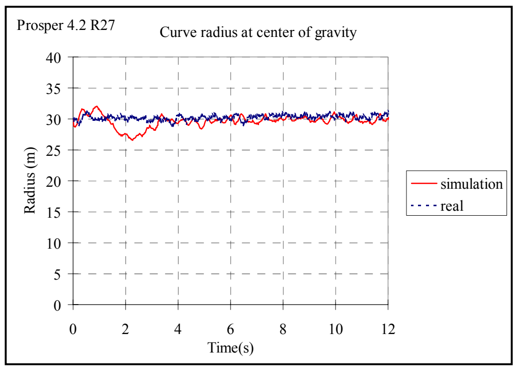



**Figure 7** Curve radius at c.o.g.

## 5.3. Results for different loads

### 5.3.1. Roll angle level validation

On figure 8, comparison between experimental results and simulation for the three lest conditions (see step 4 before) are shown.

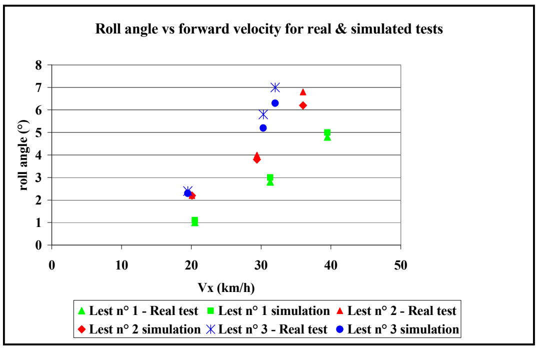



**Figure 8** Roll angle vs real/simulated tests speed

Figure 9 shows the lateral acceleration level obtained when rollover threshold is reached ; this level is also calculated for the tilt-table.

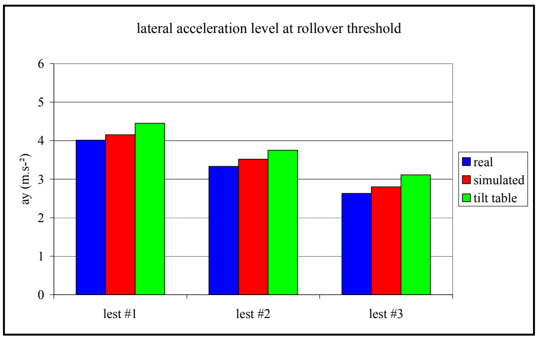


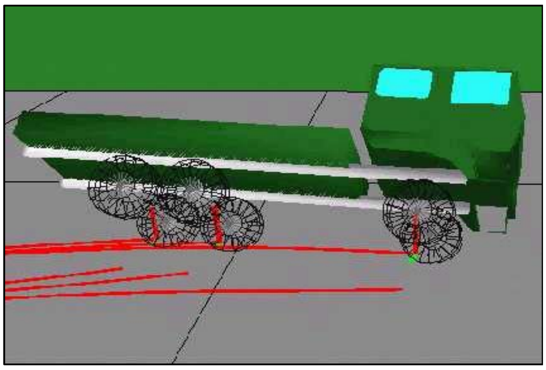

**Figure 9** Lateral acceleration at rollover threshold

For each case of load, we have a good agreement between the three type of calculation. One can note that rollover threshold obtained on tilt-table is always higher than for real or simulated lift-up conditions. We can explain this because test on tilt-table, tests are static, whereas real tests are perturbed by road roughness, defects and wind.

Comparison between video and simulation play prove the accuracy of model.

### 5.3.2. Cornering speed limits validation

Picture 4 obtained from simulation shows the case just over the limit ; for lest n°3 (highest level of c.o.g), rollover occurs on a 30m-radius at a speed of 34 km/h. At 33 km/h, a inner rear wheel has been lifted-off the ground, but the vehicle doesn't overturn, whereas at a speed of 32 km/h, all the wheels stay on the ground.



**Picture 4** Rollover simulation with PROSPER

We can see the same phenomenon on real test on picture 5 corresponding to a 30-m radius steady-state cornering, at a speed of 33 km/h. Rear wheels are is lifted up (about 15 cm).

**Picture 5** Lift up of rear wheels of the TRM10000

This good agreement between real and simulate cornering behavior, for very different cases of load, implies that this model can be considered as reliable for analyzing the problem of trucks rollover on roundabouts.

# 6. ROUNDABOUTS TESTS

## 6.1. Roundabouts observations

18 roundabouts were selected from a data base of local authorities in the west suburb of Paris.

On site measurements and observations were carried out by a technical staff.
The roundabout approach speed of 99% of truck drivers is 40 km/h. Geometric features of roundabout have no effect on this speed.
5 roundabouts were finally selected for an in depth investigation : speed profiles along the trajectory per truck type, variation of these speeds against measuring periods (day/night), variation of these speeds against climatic conditions ; variation of these speeds against vehicle type.

| | dry | drizzle | rain |
|---|---|---|---|
| **RA1** | 25,6 | 24,7 | 24,6 |
| **RA2** | 24,5 | 24,5 | 23,0 |

| | type 1 | type 4 | type 5 |
|---|---|---|---|
| **RA1** | 26,2 | 25,7 | 25,4 |
| **RA2** | 24,3 | 23,3 | 24,5 |

| | day | night |
|---|---|---|
| **RA1** | 25,8 | 24,7 |
| **RA2** | 24,3 | 24,3 |

**Table 6**

Values given in table 6 for two roundabouts are the traveling speed (in km/h) of 85% of trucks. Only a very slight difference between dry weather and rain was observed.

### 6.2. Proving ground experiment

**Picture 6** Trajectory of a roundabout (ETAS)

A lane corresponding to a typical trajectory of trucks on the roundabout 1 was materialized on the ETAS proving ground (Picture 6).

Many runs upward and downward were done by an ETAS professional driver until rear wheels lift up (picture 7).

**Picture 7** TRM 10000 rear wheels lift up

### 6.3. Runabouts experiments and simulations

Figures 10, 11 and 12 exhibit typical results obtained for the most unfavorable case.

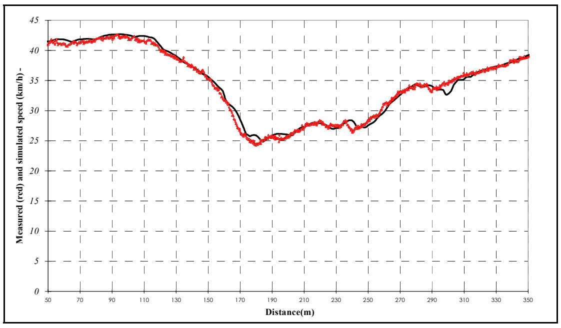



**Figure 10** Speed profile

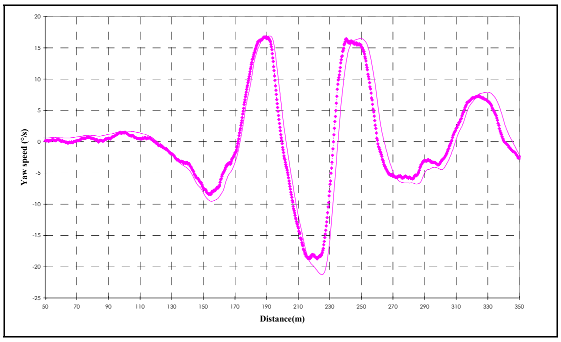



**Figure 11** Yaw comparison

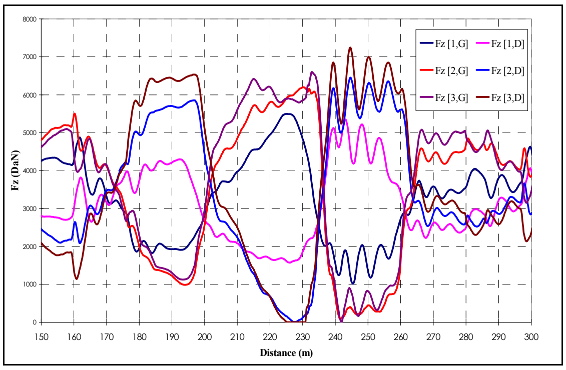



**Figure 12** Rear wheel lift up

Good agreements between measured and computed values were sometimes obtained but it is considered that improvement of suspension parameters would be necessary to ensure good agreement for the roll curves.

## 7. FINDINGS

### 7.1. A reliable Software

This experiments and numerous previous ones confirm the quality of the reliability of the simulation Software PROSPER.

Another advantage of simulation is to give some information on parameters as vertical load or slip angle, not easily measured in real conditions (figure 13).

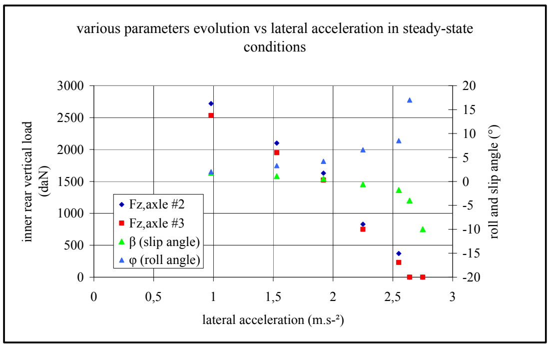



**Figure 13** Various parameters vs lateral accel. in steady –state conditions

On this figure, vertical loads (Fz) on inner rear wheels decrease quickly over a lateral acceleration level of 2m.s-² (about 1500 daN on each wheel for this level) ; at the level of 2.6 m.s-², inner wheels are lifting off, but without rollover, whereas after 2.70 m.s-² threshold, rollover is occurring.

Besides, simulation can be used to investigate the effect of different load conditions on wheel lift up. The effect of the position of the center of gravity along the longitudinal x-axis was also analyzed. Figures 14 and 15 give for an increasing lateral acceleration in steady-state condition the slip angle variation (respectively the minimum vertical load on inner tandem) for three c.o.g x-positions. The first position is the usual one, whereas the second and the third have got a change of one meter backward and forward.

On figure 14, one can note that slip angles decrease after a lateral acceleration level of 2 m.s-² ; this effect is more important for a x-position of the c.o.g forward (red points). The rollover occurs when slip angles become negative.

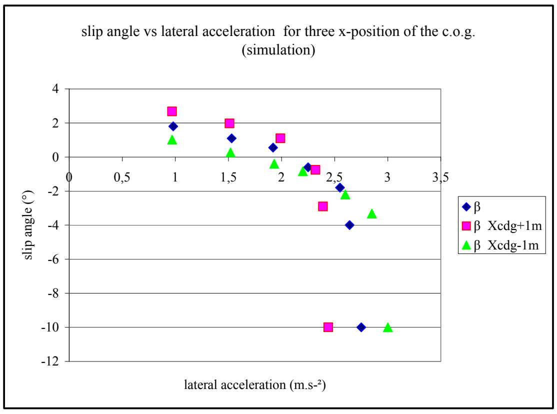



**Figure 14** Slip angle vs lateral acceleration

The vertical load on inner tandem (figure 15) present the same phenomenon ; changing the x-position of c.o.g. backward increases the rollover threshold of about 10%. Moreover, another parameter must be consider : the vertical load on the front axle must not decrease too much, because we have the risk to limit the steering capacity of the truck.

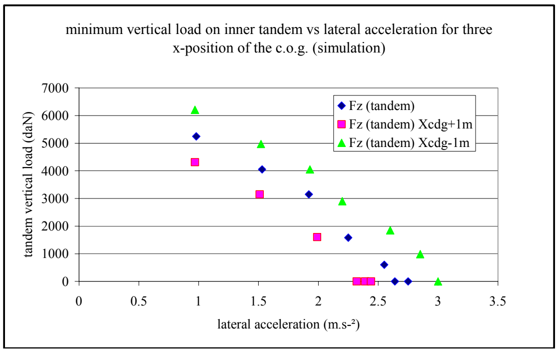



**Figure 15** Minimum vertical load on inner tandem vs lateral acceleration

## 7.2. Future developments

A new experiment with a semi trailer truck is a necessary complement.
What is sought from these simulations is to see whether on one hand advice regarding loading arrangement and on the other hand warning about bad load arrangements can be devised.
Then these results could be brought to truck driver attention for each type of vehicle.

# 8. REFERENCES :

[1] SCHAEFER, G., LECHNER, D., DELANNE, Y., SCHMITT, V., - **CALLAS :** A decisive step toward validity for 3D vehicle dynamics**.** ISATA Paper 97SAF005. 30th ISATA Conference, Florence June 1997.

[2] LECHNER, D., DELANNE, Y., SCHAEFER, G., SCHMITT, V., Méthodologie de validation du logiciel de dynamique automobile CALLAS**.** Papier SIA 970202. Congrès SIA International "La dynamique du véhicule automobile et ferroviaire" Ecole Centrale de Lyon, Avril 1997. Reprint in "Ingénieurs de l'Automobile" N°713, Mai 1997.

[3] LECHNER,D., DELANNE,Y., SCHAEFER, G. Influence of road and vehicle factors on accidents : what can be gained from driver-road-vehicle interaction models ? “FISITA 98 n° F98S185

[4] SCHMITT V., VANGRAEFSCHEPE, F, Contribution of digital simulation on the analysis of the design parameters of light and heavy vehicle Barcelona, AUTOTEST 1998

# 9. AKNOWLEGMENTS

Authors would like to thank Bernard Mathelin, Dominique Benardeau, François Saulais (ETAS) and Patrick Daburon (LCPC) whom take part in the preparation and the realization of the experiments described in this paper.